

# Comparison of Manual and Autopilot Breakout Maneuvers with Three Closely Spaced Parallel Runway Approaches

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## Abstract

This study used a high-fidelity flight simulator to explore approach operations for three closely-spaced parallel runways using autopilot and manually flown breakout procedures. An initial study investigated the concept under manual control mode only. The concept aimed to achieve visual meteorological conditions capacities under instrument meteorological conditions when landing aircraft on runways as close as 750 ft apart. This investigation studied procedures related to autopilot breakout maneuvers for triple parallel aircraft flying in an echelon formation and compared them to the manual procedures investigated earlier. All of the data collection runs had an off-nominal situation, which was either caused by the wake of the lead aircraft drifting too close to the center and trailing aircraft, or the lead aircraft deviating from its course and blundering towards the center and trailing aircraft. The location of the off-nominal situation (high/low altitude) and the position of the ownship (center or right runway) were also manipulated. Statistically significant results showed that autopilot breakout maneuvers were flown more accurately than manual breakout maneuvers. Some improved lateral separation was also observed between the paired aircraft while the autopilot was used, which could be attributed to the improved accuracies with which the breakout maneuver was flown using autopilot. On the subjective ratings, pilots experienced reduced workload, a similar level of situation awareness, and a reduced level of situational demands under the autopilot condition. Objective and subjective data from the current study extends the results from the previous research [1], with some evidence to suggest further improvement in these factors when autopilot breakout procedures are used.

## Introduction

Many US airports depend on parallel runway operations to meet the growing demand for day-to-day operations. The main objective for increasing simultaneous approaches on parallel runways is to improve the throughput of the airport. Several concepts for simultaneous approaches have focused on achieving Visual Meteorological Conditions (VMC) capacities under Instrument Meteorological Conditions (IMC) because poor weather often reduces the capacity of airport with parallel runways to half. Triple parallel runways have the potential to increase capacity especially when they are 750 ft apart. Some airports such as John F. Kennedy and Atlanta Hartsfield have adequate space between their two parallel runways to build a third runway between them such that they are all 750 ft apart. The biggest challenge with closely spaced parallel runways approaches is achieving safe operations. For runways that have greater than 3400 ft separation between them, a No Transgression Zone (NTZ) of 2000 ft between the runways provides a safety net. In the concept investigated for this study, the runways were 750 ft apart and a breakout maneuver was shown on the navigation display in the cockpit. Studies have researched missed approaches using autopilot or manual procedures for single runway airports [2] and there has been some research to compare the procedures under auto-pilot and manual flight control modes prior to a breakout for two runway operations [3]. However, no previous research has been done to compare using auto-pilot and manual flight control modes for flying breakout maneuvers on three parallel runway operations.

This paper will compare the procedures for performing breakout maneuvers for triple simultaneous procedures under off nominal conditions using either the autopilot or manual flight control mode. Several

metrics including the workload and situation awareness experienced by the pilots have been compared in this study.

The following sections of this paper describe the background research and the experimental approach that was taken to study the effect of manual and autopilot flight control modes on breakout maneuvers. Then, the results and discussion section focuses on separation between the aircraft, accuracy of flying the breakout trajectory and subjective data such as workload and situation awareness.

## ***Background***

Most of the previous research on very closely spaced parallel approaches has focused on dual runways [4] [5]. The research on triple streams of aircraft has been mostly exploratory in nature, such as investigating the effect of adding a third stream of aircraft on capacity. There have been several procedures defined for triple simultaneous approaches, and most of them define a no transgression zone or a safety net to protect against aircraft blundering or deviating from their intended path towards the other aircraft. Previous research [6] described several permutations of Simultaneous Offset Instrument Approach (SOIA) procedures for triple parallel runways. For example - an independent SOIA procedure [7] for triple aircraft arrivals procedure requires an independent monitor for each runway and has a 2000 ft No Transgression Zone established between each pair of simultaneous streams.

Breakout procedures were also defined by a concept called Airborne Information for Lateral Separation (AILS) studied by Abbott (2001) [3] at NASA. They explored procedures where the flight control mode prior to the breakout was either autopilot or manual. The breakout procedure was always performed under manual flight control modes. They found that if the pilots were flying under an auto pilot control mode prior to the actual breakout maneuver, they took longer to respond to the breakout.

Several researchers have investigated the effect of flight control modes on workload and errors. Casner [2] also explored the effect of flight control mode on different phases of flight that included missed approaches for single runway operations, which are in some ways similar to the breakout maneuver. Among the other variables manipulated in the study were the

navigation methods (VOR-Very high frequency Omni Range or GPS - Global Positioning System). He found that overall workload was higher in manual flight mode as compared to the auto pilot for the missed approach phase of flight. The author also found that on the subjective survey items, the pilots indicated a “strongly agrees” to autopilot reducing their workload (4.63 on a scale of 5). They showed preference for using auto-pilot during periods of high workload (4.63 out of 5). Similarly, they also showed mid-level preference (3.38 on a scale of 5) towards using autopilot for missed approaches.

The authors of the current study also explored triple runway procedures for breakout maneuvers conducted under manual flight control mode. They found that pilots experienced high workload and a reduction in situation awareness because they had to focus too much attention on flying the breakout maneuver shown on the navigation display using the flight director on the primary flight display [1]. The current paper explores the differences in flying the breakout maneuver using the autopilot control mode, as compared to the manual mode with three closely spaced parallel runways.

## **Experimental Approach**

### ***Airport and Airspace Design***

The experiment used a fictitious airport (KSRT) loosely based on the current Dallas/Fort Worth International Airport (DFW) layout and operations except for three parallel runways that were set to be 750 ft apart. Because the simulation focused on TACEC approaches to very closely spaced parallel runways using south flow scenarios, only the west side runways (18L, 18C and 18R) were used. The outside runway (currently 18R) was moved inward to create 18C with a 750 ft separation between the runways and a third 18R was also added at 750 ft from 18C. All three of the runways were assumed to be equipped to a CAT-IIIB level.

### ***TACEC Procedures***

Terminal Area Capacity Enhancing Concept [7] (TACEC) allows for any aircraft arriving from any of the four arrival meter fixes (NE, NW, SE, and SW) to be paired for a simultaneous parallel landing, based on aircraft characteristics and relative timing criteria. The three paired aircraft flew their assigned 4D trajectories with a high level of accuracy to meet timing constraints

at the coupling point and to ensure wake safety throughout the approach. TACEC assumes augmented Global Positioning System (GPS) and ADS-B (Automatic Dependent Surveillance-B).

TACEC calls for the three aircraft to be paired at meter fixes located near the edge of the terminal airspace, normally 40-60 nmi from the airport [8] and given TACEC-assigned 4D arrival trajectories to the runway. Flights in the simulation began 25 nmi from the airport, assuming they were already paired/grouped. Routes to the airport included approach and departure routes, and procedures were defined to be, similar to those at the DFW airport. This study focused on arrivals, and no departures were included in the traffic.

The coupling point, which refers to the point at which the speed of the multiple aircraft becomes dependent, or “slaved” to one another, is defined at 12 nmi from the threshold of the runway. From that point onward in the simulation, the center aircraft precisely maintained 12s spacing behind the lead aircraft, and the right aircraft maintained 24s behind the lead aircraft using a speed algorithm to avoid the wake and for safe separation. The approach paths of the two trailing aircraft were at a slewed angle from the center of the runway- six degrees for the aircraft on the center runway and 12 degrees for the aircraft on the right runway, when the aircraft were 25 nmi from the threshold. All three aircraft turned straight and parallel to each other at about 2 nmi from the runway.

Onboard automation, based on ADS-B, monitored the three aircraft for potential emergency situations. The automation displayed a predicted hazardous zone for the wake generated by the lead and center aircraft in the cockpits of the second and third planes. ADS-B lateral position and intent information was used to detect and display any deviation from the proposed approach path that would encroach on either of the trailing aircraft. Visual and aural alerts were given to the pilots when the lead-aircraft’s blunders or wake presented a dangerous situation to the trailing aircraft.

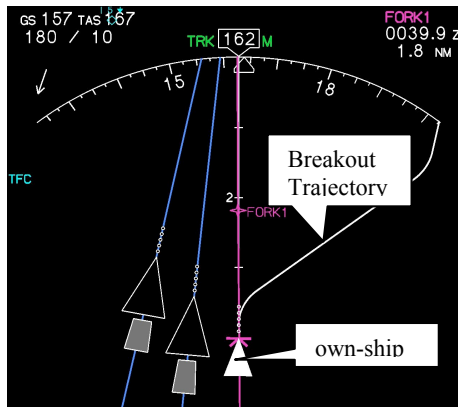
The navigation display depicted a breakout trajectory after the aircraft crossed the coupling point. This breakout trajectory was dynamically generated and considered wake, traffic, buildings and terrain of the airport surroundings. When the breakout was required at different altitudes on the arrival path,

different bank angles for the breakout maneuvers were used and the curvature of the breakout trajectory changed on the navigation displays. The pilots flew the breakout trajectory manually using the flight director when they received an aural and visual alert under the manual flight control mode condition. In the auto-pilot condition, they flew the breakout trajectory without disengaging the auto-pilot.

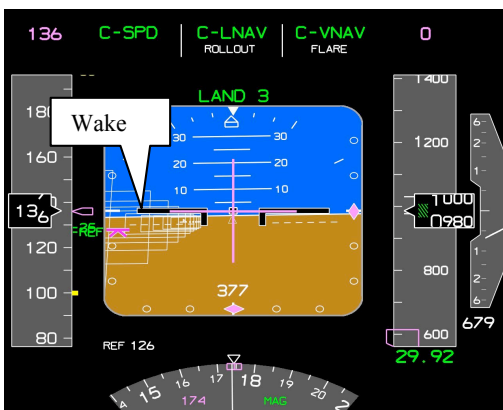
### *Displays*

The displays were similar to the displays used for the study of two runway very closely spaced parallel approaches [4] and were based on previous research associated with flight deck displays [8] [9]. The Navigation Display (ND) and Primary Flight Display (PFD) are shown in Figures 1 and 2. The displays show wake and trajectory information along with standard flight instrument data.

Information regarding coupling of aircraft is also shown on PFD. After crossing the coupling point and the pilot’s prior acceptance of coupling with the lead aircraft, the flight mode annunciation changes to show that the three aircraft are coupled for speed (C-SPD), coupled for lateral navigation (C-LNAV) and coupled for vertical navigation (C-VNAV). The two trailing aircraft were coupled with the lead aircraft. The autopilot of the trailing aircraft flew the approach; the pilot primarily monitored the aircraft performance and the displays for the remainder of the flight. If the wake of the adjacent aircraft drifted within one wingspan of the own-ship aircraft, the color of the wake hazardous zone of the lead aircraft on the display turned to yellow, and then turned red when the apex of the aircraft was in the wake. Similarly, if the lead aircraft deviated from the planned trajectory towards the following aircraft’s path by 60 ft, the lead aircraft symbol turned yellow, and then red when the lead aircraft deviated by 120 ft. The red warnings, accompanied by an aural alert “breakout, climb” required a mandatory breakout, which the pilots flew manually. When the pilots pressed the Take-Off-Go-Around (TOGA) switch, the breakout trajectory, which had been displayed to the pilot in white, became the active route, and was then displayed in magenta for both the flight control modes.



**Figure 1: Navigation Display (ND) during final approach**



**Figure 2: Primary Flight Display (PFD)**

### Advanced Concept Flight Simulator

The human-in-the-loop experiment studied breakout maneuvers using auto-pilot and manual flight control mode for triple TACEC approaches in the Advanced Concepts Flight Simulator (ACFS), which is located at NASA Ames Research Center. The ACFS is a motion-based simulator that represents a generic commercial transport aircraft, enabling it to be reconfigured to represent future aircraft. It has the performance characteristics similar to a Boeing 757 aircraft, but its displays have been modified to study different advanced concepts. In this study, the cockpit displays described in the previous section were integrated with the flight display systems in the cockpit. The visual systems offer a 180 deg horizontal and a 40 deg vertical field of view. This simulator is capable of providing various visibility conditions and was set to IMC for this experiment.

### Study Design

Four factors were manipulated in this study on the TACEC concept for triple runways. The primary factor, which is the most pertinent to the focus of this paper, is flight control mode, with two state values - manual or autopilot mode under which the breakout maneuver was flown. The second factor was the cause of the breakout maneuver – wind causing the wake of the lead aircraft to drift towards the following (center) aircraft, or the lead aircraft deviating from its original path and towards the trailing aircraft. The third factor was the location of the off-nominal situation, which was above 500 ft, or between 200 ft – 500 ft AGL. The fourth factor was the position of the ownship or the simulator which could either be approaching the center or right runway (with the lead aircraft approaching the leftmost runway). All runs had an off-nominal situation that required a breakout maneuver. A total of 16 runs were performed for each participant, 8 of which used the manual flight control mode to fly the breakout maneuver and the rest used the autopilot for the breakout maneuver. The table shows the test matrix, which was repeated to get 8 autopilot and 8 manual flight control mode runs. Repeated runs were made for each breakout cause, breakout location, and position of the aircraft under each flight control mode.

|                                      | Breakout Cause:<br>Wake | Breakout Cause:<br>Aircraft Deviation |
|--------------------------------------|-------------------------|---------------------------------------|
| Breakout Location:<br>> than 500 ft  | Center/Trailing Ownship | Center/Trailing Ownship               |
| Breakout Location:<br>200 ft -500 ft | Center/Trailing Ownship | Center/Trailing Ownship               |

**Table 1 : Test matrix repeated for flight control mode.**

### Hypotheses

Based on previous research conducted on flight modes [2], we predicted that there would be reduction in workload and improvement in situation awareness under the autopilot control mode, as compared to the manual control mode, for flying the breakout

trajectories. We also predicted increased aircraft separation and improved breakout trajectory accuracy with autopilot, as compared to the manual breakout procedures, due to the precise nature of the autopilot mode.

### ***Participants***

The participants were three recently retired pilots from commercial airlines; all were male and they all had experience with glass cockpits. Their average experience as a pilot was about 38 years. Their average number of years since retirement was less than two.

### ***Experimental Procedure***

The study ran in two parts: the first part collected data on manual flight control mode with three pilots and the second part had the same pilots who participated in the auto-pilot flight control mode fly the breakout maneuvers. At the beginning of the experimental run for both manual and auto-pilot set of conditions, the pilots were familiarized with the project, the concept, and the new displays in the cockpit. The pilot received a demonstration of the ACFS and hands-on training on the flight deck displays and related procedures.

Since procedures for triple Very Closely Spaced Parallel Runways (VCSPR) were being explored in this study, each pilot flew the ACFS in the left seat (as captain) along with a confederate who acted as the first officer for both the flight control modes – manual and auto pilot. Prior to flying the breakout maneuver, the role of the pilot was to fly in auto pilot mode and monitor the displays to check separation with the lead aircraft and with wake. Prior to the coupling point the pilots heard a chime, saw the acknowledgement button light up, and received a “TACEC Coupling” message on the lower Engine Indicating and Crew Alerting System (EICAS) display.

At this point the pilots pressed the accept button. They flew as the center or as the trailing aircraft and both of those aircraft were coupled with the leader aircraft on the left most runway. They were coupled with the leader’s speed and continued to monitor the separation between the three aircraft. The flight mode annunciation also changed to show that the two aircraft were coupled for speed (C-SPD), coupled for Lateral navigation (C-LNAV) and coupled for Vertical navigation (C-VNAV). If the pilots received a visual

and aural alert from the displays they were required to perform a breakout maneuver.

Under the manual flight control mode for flying the breakout maneuver, the pilot would press the TOGA switch, disengage the autopilot, leave the auto throttle on, and fly the breakout trajectory shown on the ND. Pressing the TOGA switch would capture the breakout trajectory, and the pilots used the flight director to fly the trajectory. They flew different breakout trajectories at different altitudes, with the breakout above 500 ft altitude requiring an initial bank angle of 30 deg, and the breakout at altitudes between 200-500ft requiring an initial bank angle of 10-deg. They had an initial heading change of 20-deg if they were the center aircraft on 18C and a heading change of 40-deg if they were the trailing aircraft on 18R. In all the above cases, the aircraft had to climb to 3,000 ft as a part of the break out procedure. The pilots then followed the ‘S’ shaped breakout trajectory displayed on the ND. The trajectory was ‘S’ shaped so that the final leg of the trajectory became parallel to the runways. The final leg of the breakout trajectory was 1.5 nmi abeam for 18C and 3 nmi for 18R.

Under the auto-pilot flight control mode, the only difference from the above procedures was that the pilot pressed the TOGA button to execute the breakout maneuver, and did not disengage the auto-pilot. Rest of the procedures for the auto-pilot mode were the same as that for the manual mode.

### ***Traffic Scenario***

The traffic scenario had three aircraft: (1) The ACFS (B757) was always one of the two following aircraft (center or trailing) in the triplet, and the other two aircraft were scripted, depending upon the experimental condition, and (2) the leader aircraft was a Boeing 747-400, which was prerecorded and scripted for this study and landed on 18L under nominal conditions. The pilot who flew the ACFS simulator always landed on either 18R or 18C or performed the breakout, depending upon the simulator position for the particular data collection run. Operationally, the trailing aircraft should be upwind of the cross wind, but this is not always possible so all scenarios included adverse crosswind. It should also be noted that larger aircraft would ideally be the trailing aircraft (from an intra-echelon perspective); a leading ‘heavy’ aircraft in the upwind position represents the worst-case scenario for this concept.

### ***Tools used for Data Collection***

Several tools were used for collecting subjective data from the pilots. All participants completed a demographic survey before the simulation runs were conducted. The survey collected information about the pilots such as their age, experience and number of hours flying different aircraft types, any experience with SOIA approaches, and experience using personal computers.

All pilots were asked to complete a Post Interaction Survey at the end of all the runs. This survey allowed them to rate the information content and the usability of the displays.

The participants completed the NASA Task Load Index (TLX) rating scales [10] after each simulation run but did not complete the pair-wise scale comparison included as part of the TLX, so the six scales were analyzed separately.

Pilots also completed the Situation Awareness Rating Tool (SART) [11]. The SART gathers a participant's rating of situation awareness (SA) for the preceding period of time on ten different scales. Each scale has 7 points, with the end points representing opposite ends of the construct. Participants circled the point on the scale that most closely represented their experienced level of SA. The ten SART ratings together with the TLX ratings were gathered from every participant at the end of each simulation run.

In addition to the assessment instruments described above, the flight simulator's digital data collection system was used. A host of objective flight data from each of the simulation runs was collected on the variables pertinent to the hypotheses of the experiment. All collected data were indexed with a common timestamp, which was used as the basis of time synchronization as it updates in real-time while the simulation run advances. All digital data were collected at a rate of 30 Hz.

### **Results and Discussion**

Statistical analysis of the study-data focused on three areas: (1) the flight simulator's digital data collection outputs, (2) the pilot participants' workload and situation awareness assessments, and (3) verbal feedback provided by the pilot participants at the end of the simulation runs.

As a means of controlling for the possible confounding influence of variables that could impact

the results pertinent to the current investigation, other factors were built into the statistical analysis paradigm. More specifically, autopilot vs. manual breakout differences were analyzed along with 3 other independent variables using a 4-way repeated measures analysis of variance (ANOVA) procedure. These three additional variables - cause of breakout, location of breakout, and position of ownship were analyzed in a previous study [1], as they were pertinent to that investigation, and results on these factors were fully addressed and reported. However, since the focus of the current paper is on autopilot vs. manual breakout differences, only the results on this factor will be reported.

#### ***Aircraft Separation from Breakout through 30 Seconds Past Breakout***

The dependent measure of aircraft separation is defined as slant range, also known as the displacement distance between two aircraft. Analysis of aircraft separation as it changes over time from breakout point was implemented, to determine if there were any instances of unsafe separation between aircraft during the most critical phase of the breakout maneuver, i.e., the time span that immediately follows breakout point, defined as breakout time through 30 seconds past breakout time. Separate analyses were performed in comparing (1) Leading and center aircraft separation, and (2) Center and trailing aircraft separation. Table 2 shows summary statistics of the combined autopilot and manual breakout data as they changed over time originating from breakout point.

As indicated in Table 2, there is a clear trend towards increased separation between each of the two pairs of aircraft analyzed, with some overall increase 15 seconds past breakout, and a larger increased separation at 30 seconds past breakout.

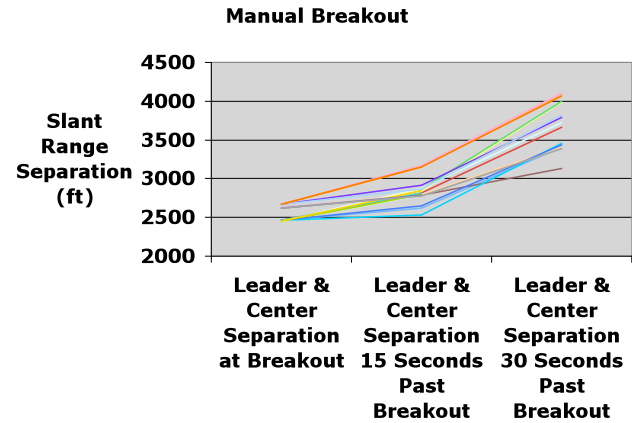
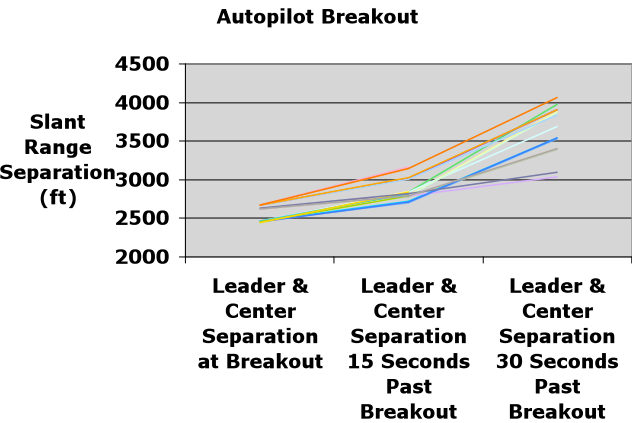
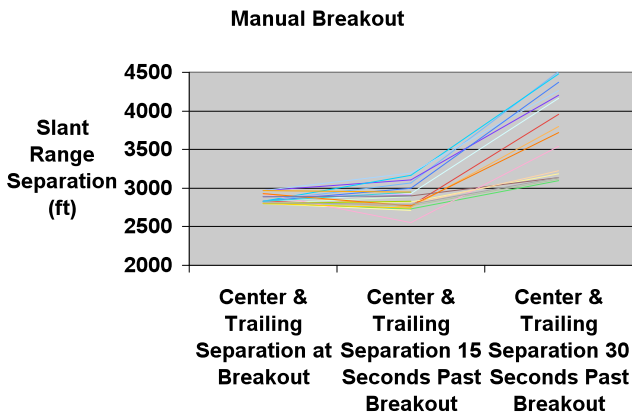
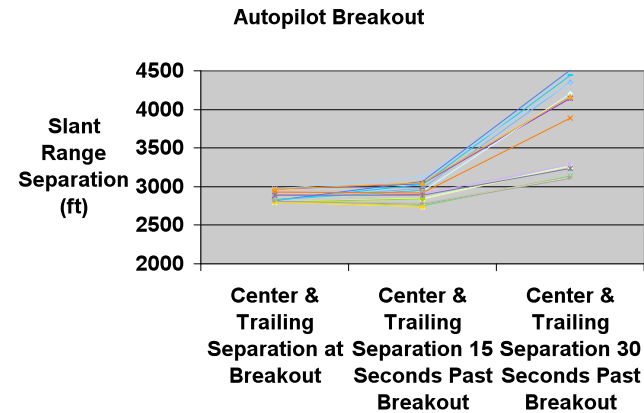
Figures 3 through 6 show the same aircraft separation data displayed in Table 1, broken down by manual vs. autopilot breakout conditions.

Generally, Figures 3 through 6 show similar distribution patterns of separation data between autopilot and manual conditions for each aircraft pair analyzed. Also, the behavior of the separation data as it changes over time, broken down by autopilot and manual conditions, is very similar to the overall separation distribution shown in Table 1 with a clear trend towards increased separation between each of the two pairs of aircraft analyzed, with some overall

increase 15 seconds past breakout, and a larger increased separation at 30 seconds past breakout. The only apparent exception to this trend, shown on several individual time-series in Figures 5 and 6, indicate a relatively small decrease in separation 15 seconds past breakout, prior to increased separation 30 seconds after breakout. This behavior occurred only occasionally, and only with the center/trailing aircraft pair.

| <u>Leader &amp; Center Separation</u>   | Mean (ft) | SD (ft) | Max (ft) | Min (ft) |
|---|-----------|---------|----------|----------|
| Breakout Point                          | 2551      | 98      | 2674     | 2447     |
| 15 Seconds Past Breakout                | 2859      | 150     | 3172     | 2534     |
| 30 Seconds Past Breakout                | 3654      | 308     | 4106     | 3038     |
| <u>Center &amp; Trailing Separation</u> |           |         |          |          |
| Breakout Point                          | 2855      | 61      | 2968     | 2796     |
| 15 Seconds Past Breakout                | 2888      | 133     | 3192     | 2552     |
| 30 Seconds Past Breakout                | 3734      | 546     | 4509     | 3094     |

Table 2. Aircraft Separation Following Breakout (combined manual and automated condition)



Figures 3-4. Aircraft Separation Following Breakout: Leader & Center Slant Range Under Autopilot and Manual Conditions (each time-series represents one simulation “flight”) N=8

Figures 5-6. Aircraft Separation Following Breakout: Center & Trailing Slant Range Under Autopilot and Manual Conditions (each time-series represents one simulation “flight”) N=8

These data suggest that this particular trend, which occurred under both manual and autopilot conditions, reflects the complex geometry of the breakout maneuvers. Specifically, the center aircraft needs to separate itself from the leader aircraft towards the trailing aircraft, which may initially decrease separation for a very short period of time. Even so, during this critical window of time, there were no cases where the slant range between either of the aircraft pairs was less than 2400 ft, indicating zero instances of unsafe separation. These data compare favorably with the data collected by the FAA's MPAP study [12], which defined a test criterion violation (TCV) as 500 ft of separation between aircraft. Using the same definition, a TCV was not observed at any time, at or beyond breakout. Clearly, the objective evidence shows significantly larger separation than the TCV value indicated in the MPAP studies.

Further, possible differences between autopilot and manual conditions were assessed on the dependent measure of slant range separation 15 seconds past breakout. ANOVA results comparing the two study conditions indicate some increased separation between the paired aircraft when the autopilot was used. Table 3 provides summary statistics and ANOVA results pertinent to this finding.

| Aircraft Pair                            | Condition | Mean(ft) | SD (ft) |
|--|-----------|----------|---------|
| Leader & Center:                         | Autopilot | 2867     | 139     |
|  | Manual    | 2849     | 163     |
| *Center & Trailing:<br>(F=20.63; df=1,2) | Autopilot | 2902     | 110     |
|  | Manual    | 2875     | 154     |

**Table 3. Autopilot vs. Manual Breakout Effect on Aircraft Separation 15 s Past Breakout (\* p<0.05)**

These results seem to indicate that either the autopilot or manually flow breakout procedures could provide a basis for safe breakout maneuvers for the concept under study. In addition, ANOVA results indicated some added safety benefit, in terms of increased aircraft separation, provided by flying the VCSPR breakout using autopilot.

### ***Accuracy of Breakout Trajectory: Cross Track and Track Angle Error***

Trajectory accuracy is measured by the actual ownship/simulator position against the breakout trajectory generated by the system and displayed on navigation display in the cockpit (see Figure 1) averaged across time. Two measures of ownship trajectory particularly sensitive to breakout maneuvers include cross track error and track angle error. For each flight simulation run, cross track error and track angle error were averaged across time from the breakout point to the end of the flight. A two-way repeated measures ANOVA yielded a main effect of condition (autopilot vs. manual) on each of the two dependent measures. Both of these results are consistent with respect to the directionality of the means across both track angle and cross track error. Less cross track error and less track angle error were observed under the autopilot breakout condition, as compared to the manual breakout condition. ANOVA summary statistics from this analysis are listed in Table 4.

|  | Mean     | SD       |
|--|----------|----------|
| * Cross Track Error:<br>(F=72.30 df=1,2) |          |          |
| Autopilot                                | 28.44 ft | 19.36 ft |
| Manual                                   | 74.49 ft | 78.91 ft |
|  |          |          |
| *Track Angle Error<br>(F=28.80;df=1,2)   |          |          |
| Autopilot                                | 0.88 deg | 0.52 deg |
| Manual                                   | 2.27 deg | 1.98 deg |

**Table 4. Autopilot vs. Manual Breakout Effect on Ownship Cross Track and Track Angle Error (\* p<0.05)**

The pilots flew the breakout trajectories with higher precision under the autopilot condition, which would make sense, due to the increased level of automation accuracy that the autopilot provides during breakout. This result is consistent with the results that Casner [2] found where the use of auto-pilot for missed approaches led to a smaller average number of errors. Also, since the autopilot was used to fly the breakout procedure, the pilots would be able to focus more attention on the information provided by the displays,

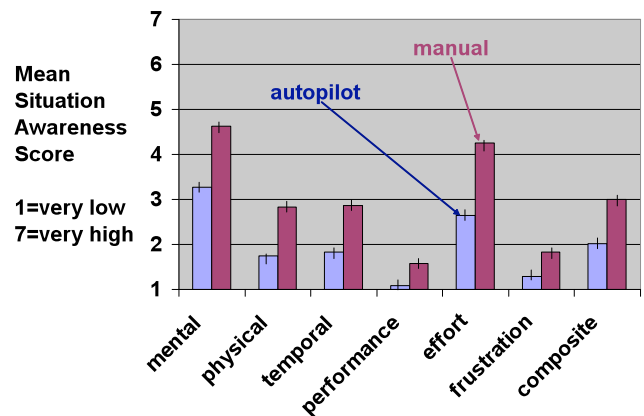


rather than manually flying the breakout, which would necessarily have the effect of increasing pilot situation awareness. This dynamic will be discussed in greater detail later in this paper.

### Workload

Participants completed the NASA TLX workload questionnaire after every run. Data were collected on each of the six TLX workload measures, and a variable measuring overall workload combining all six of these measures was derived, for a total of 7 workload measures. This overall workload variable, also known as the “composite” measure, once derived, was then scaled down to match the 1 to 7 scale for direct comparison with the other six measures. Also, the “performance” measure was analyzed on an inverse scale, so a higher score would actually mean less performance. Results on all 7 of these measures, comparing autopilot vs. manual breakout results, are summarized in Figure 7.

Results shown in Figure 7 indicate that pilot workload was consistently lower in autopilot breakout runs as compared to manual breakout runs in all of the 6 workload measures, as well as the overall workload composite measure. This was expected, since manual breakout procedures require the pilots to manually fly the ownship according to the breakout trajectory while also monitoring the displays. Under autopilot breakout, the pilots were mostly concerned with monitoring the displays, thereby decreasing workload and enhancing situation awareness, since the actual flying of the breakout maneuver was taken over by the automation. In particular, the physical workload and effort levels decreased for the auto-pilot condition, which is also consistent with results from the Casner study [2]. It should also be noted that workload measured across all scales and conditions was found to be manageable, at low to moderate levels (Figure 7). Hence, workload seems to be low enough to be reasonable, but high enough to prevent tedium and vigilance decrement based on criteria established by previous research [13].



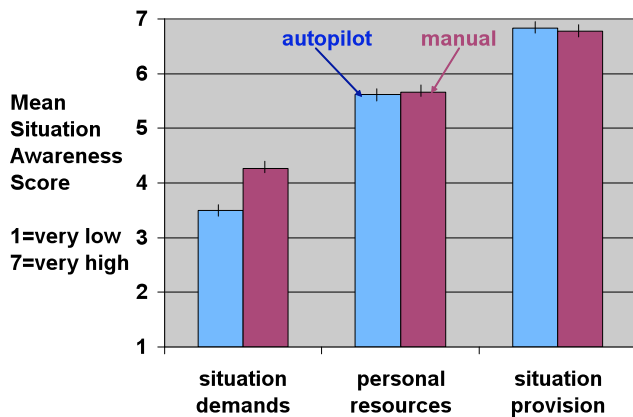
**Figure 7. Effects of Autopilot & Manual Breakout on Pilot Workload Measures (error bars represent  $\pm 1$  standard error)**

### Situation Awareness

The SART scale, mentioned earlier, measures situation awareness on ten scales [11]. Participants provided ratings on each of these ten scales after every simulation run. All collected SART data were then used to derive three broader categories concerned with a) the demands of the situation b) the ‘supply’ or personal resources that the participants have to bring to the situation and c) situational provision that the situation provides in the form of information through displays. The first broad category combines the three SART scales - instability, variability and complexity of the situation. The second broad category of personal resources combines the SART scales on alertness, spare mental capacity, concentration, and division of attention. The third broad category, situation provision, combines the three SART scales on information quantity, information quality, and familiarity. After all data were collected and the three broader categories were derived, results were then scaled down to range from 1 (very low) to 7 (very high).

Figure 8 shows situation awareness results on the three derived variables, comparing autopilot and manual breakout conditions. It was found that the situation demands of the autopilot breakout runs were lower than those of the manual breakout runs. This result is consistent with our result of lower pilot workload levels in the autopilot condition, since workload correlates with the three SART subscales which form the broader variable of situation demands. Again, the manual breakout condition requires that pilots safely maneuver the aircraft by following the

breakout trajectory *and* maintain adequate situation awareness, which equates to more situation demands than those of the autopilot breakout condition. Results on personal resources indicate almost no difference between the two breakout conditions. This may be due to the anticipation of a breakout anytime, which required equal levels of alertness and concentration across both conditions. Likewise, there was almost no difference between the two breakout conditions in situation provision, suggesting equal amounts of information quantity, information quality and familiarity throughout the course of the simulation runs.



**Figure 8. Effects of Autopilot & Manual Breakout on Pilot Situation Awareness Measures (error bars represent  $\pm 1$  standard error)**

Finally, relative to the possible range of values for each of the three broader situation awareness measures, Figure 8 indicates high levels of personal resources and situation provision, with moderately low levels of situation demands across both breakout conditions, suggesting that situation awareness was maintained throughout the course of the current investigation, providing additional support for the efficacy of the TACEC concept.

## Summary and Conclusions

Triplet aircraft procedures were investigated in a high fidelity human-in-the-loop simulation incorporating new tools and technologies involving very closely spaced parallel runway operations under both autopilot and manually flown breakout procedures. The results indicated that the autopilot breakout procedures were flown with greater accuracy and better separation than the manually flown breakout

procedures. Also, the pilot participants maintained higher levels of situation awareness and lower levels of workload in the autopilot condition as compared to the manual condition. Also, data analysis comparing both study conditions resulted in additional improvement on all of the dependent measures of interest under the autopilot breakout condition.

An analysis of aircraft separation during breakout, depicted that, the observed slant range between aircraft never fell below 2400 ft., which is well above the FAA's MPAP test criterion violation threshold between aircraft [12]. A statistically significant result was also observed, indicating increased separation under the autopilot breakout, as compared to manual breakout procedures, thus upholding our hypotheses. Analysis of cross track and track angle error indicated statistically significant results between the autopilot and manual conditions, indicating increased trajectory accuracy under the autopilot breakout procedures as compared to manual breakout.

The pilots experienced lower workload and situational demands placed on them during autopilot breakout as compared to manual breakout. While realizing these differences, the results also indicate that workload was manageable, and an adequate level of situation awareness was maintained across both conditions. Overall, our hypothesis regarding autopilot breakout procedures decreasing workload and increasing situation awareness, and also showing increased separation as compared to the manually flown breakout procedures were upheld. While more research is still necessary especially with trajectory errors and uncertainties that were not considered in the paper, these results attest to the potential promise of this concept for possible integration into the future NextGen operational environment.

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